Stochastic Mathematical Model for Food Waste Reduction in a Two-Level Supply Chain for Highly Perishable Products

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***Abstract*— This article introduces a stochastic mathematical model for food waste reduction. Both consumers' and retailers' food supply chains are considered. The model describes consumer demand and consumption patterns, as well as retailers' inventory replenishment policies, and considers the amount of food waste at each level. Primary data was collected by questionnaires to gain descriptive statistics about food waste in a particular area in Thailand. We also calculated the probability distribution of the coefficients of consumers' consumption and buying behaviours to be used as our model input. The mathematical relationships between the entities were simulated on a spreadsheet. A specific inventory replenishment policy was applied to the system and assuming the lifetime of the products to be one day; i.e. highly perishable products only. The results show that the size of the unit sales has an impact on the total food waste produced by the supply chains. The best unit size of a sale can be properly determined. The stochastic mathematical model presented in this article is unique to previous published work as it considers stochastic consumption and buying behaviours and the total of food waste values from the 2-level supply chains.**

***Keywords*—** *Food waste, Supply chain, Survey, Mathematical model, Spreadsheet model*

1. Nomenclature

Food waste at the consumer's level is food that consumers bought for consumption but could not consume the whole portion. While the leftover food may be kept for subsequent consumption, it does have a limited life, and deteriorates, or reaches its expiry date, and thus becomes food waste.

Food waste at the retailer's level is food that retailers have offered for sale to customers but has deteriorated, or has reached its expiry date, and has become unsalable, and thus becomes food waste. In our study, highly perishable foodstuffs only were considered.

2. Introduction

According to authorities, such as the Food and Agriculture Organization of the United Nations, FAO, the world is facing a food security crisis. An important facet of this situation is the reduction of food loss by various means, such as deterioration in storage or transporting, and, equally important, reducing food waste. It is estimated that 1.3 billion tons of food is wasted, globally, each year, which is approximately one-third of all food production for human consumption [1].

The food waste problem affects both the economics of the entire supply chain, and the environment. For consumers, food waste means wasted food purchasing outlays, and creates waste disposal problems, the impact of which grows according to the population size and density. Landfill availability, garbage collection manpower, equipment and processes, collection, transport and disposal costs are all matters of growing concern. Environmentally, rotting food produces methane, which has 23 times more influence on the greenhouse effect than CO2 [2].

At the supplier level, resources are also wasted when food produced and transported is wasted. At all levels, at the primary producer level, the wholesale level, and the retail level, food waste is a significant problems for many and various reasons.

Most studies have presented data on food waste at the broad view, from the worldwide vista down to the international and national levels [1], [3]-[5]. These articles use data from governmental and agency reports, and research conducted at the macro or economy level. Policies and strategies for reducing food waste have usually been based on these broad data. However, little discussion can be found on the problem as the local market and end-consumer level. The retail sectors, particularly, operate under more dynamic circumstances, with daily decision making and actions in regard to food

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delivery, food sales, and food waste. Highly perishable foodstuffs with very short shelf lives, a variety of sales units, and the effects of expiry dates, both legal and salability effects, are inherent in the food waste aspects of the consumer and retailer food supply chains. Our study is based on these factors.

By spreadsheet modeling the relationships between entities are demonstrated by exploiting the built-in functions and calculating ability of the spreadsheet software. Spreadsheeting has been used to support decision making in many disciplines for many years now and the sophistication, power and ease of use of spreadsheet software has significantly advanced in that time. 'What-if' questions can be asked, and various scenarios developed based on the underlying data which may be retrieved from an external database, for instance [6]. Notwithstanding the long history of spreadsheet use in a wide variety of industries and applications, a search on past publications on the ISI database found only 45 articles discussing modeling of systems, applications or data based on combinations of the keywords "food waste", "model" and "supply chain", and none of these articles used mathematical or spreadsheet modeling for reducing food waste in retail or consumer supply chains.

In this paper we present descriptive statistics based on data collected from a survey on food waste in a sample area in Thailand. The particular area is a generally semi-urban and rural area, but surrounds a major university with a large student population, served by many small restaurants, small 24 hour supermarkets, and a number of open markets selling meat, fish, vegetables and other foodstuffs.

The data from the survey was statistically analyzed for the distribution functions of the buying and consumption behaviours of the consumers. A new mathematical model for total food waste reduction in a two level supply chain, modeled in spreadsheet software, is presented. The model was tested using the data from the survey to demonstrate the efficacy of the model for informing policy decisions at the operational level.

3. Literature review

The Food and Agriculture Organisation of the United Nations (FAO), in a 2011 publication [1], summarized the causes of food loss and food waste at each level of the food supply chains. At the broader national level, a lack of proper storage and transport facilities for food products is a major problem which has been identified as being especially problematic in under-developed and developing countries and has been the subject of national policies. At the consumer and retailer levels, however, the two main causes of food waste have been identified as (a) too much diversity of products (by brand, for example) of the same type, and (b) the consumption and buying behaviours of the consumer. These causes are especially true for developed countries where people have higher incomes and demand diversity and availability of a wide range of goods. It is these latter levels that this research particularly considers.

Various authors have commented on and discussed the matter of food waste in the different level of the food chain. Ref. [3], for example, discussed the different definitions of food waste put forward by different authors and considered appropriate at the different levels of the supply chain. Particularly discussed has been the level of post-harvest and supply chain technology which affects food loss and food waste. These authors reviewed previous work on estimates of post-harvest losses of both perishable and non-perishable food crops, and also made their own estimation. Household food waste is seen as an important factor contributing to overall food waste, and household demographics, such as the number of family members, ages of family members, household income, eating culture and price, have been considered. Ref. [7] suggested a definition for food loss and waste and how to use such definition to increase the robustness and comparability of the Life Cycle Assessment studies.

Some studies have used regression modelling to evaluate and estimate the important factors that lead to food waste [4], [8]. Again, demographic factors, such as gender, education, employment and location, were considered. Other important factors affecting consumer behaviour and purchasing patterns include the ability to understand the information on the labels, including dietary information, ingredients lists, including chemicals, food storage requirements and particularly expiry dates, use-by dates or "best before" dates, which terminology depends on location. Other factors more directly under the control of the consumer include orderly shopping behaviour with pre-prepared shopping lists, correct knowledge of

proportion of ingredients to be used in food preparation, transforming leftover food and ensuring proper storage in the home, such as refrigeration, freezer, or dry storage. Factors related to retailers included providing small unit sizes for sale and also having proper storage facilities. Ref. [9] made a structural equation model to explain the complexity of the behaviour of youth consumers living in Italy and Spain towards food waste. The result showed that marketing and sale promotions influence the participants buying behaviour, which underlining that retailers played an important role in avoiding food waste generation.

Although such regression models provided us with a view on how each factor affects the amount of food waste generated, the models did not show how the a multi-level supply chain reacts and interacts and therefore could not be used to set retailing policies necessary to reduce food waste across both the consumer and retailer levels.

A number of articles focused on how to lessen food waste by diverting the food path. Ref. [5] examined 30 case studies and created a conceptual model to re-route excess food from consumers back into the food chain for consumption or other usage. Similarly, Ref. [10] used a mathematical model to find the best time for retailers to donate their left-over, waste produce to charitable organisations for consumption by the clients of those charities. The objective was to maximize the benefits to the recipients while minimizing the cost of disposal, and also the cost to the recipients. Ref. [11] used stochastic model to maximize the expected total volume of crops donated to the Food Bank, where donation calls arrive randomly as well as the availability volunteers that are making collection trips. The result could be applied to make national policies that solve two concurrent problems namely food insecurity and food waste.

Ref. [12] established a discount price for a perishable product according to its declining quality. The authors used a mathematical model with a maximized profit objective. This model is useful for the retail sector. Ref. [13] applied simulation model to show the usefulness of technical, logistical and marketing interventions on preventing chilled-food waste at retail stores. Low and fluctuating demands, buying behaviour, the order lead time, a fixed unit sale, and a short use-by date were identified as waste drivers. However, Ref. [12] and Ref. [13] only considered what is best at the retailer level of the supply chain. Consumers, however, frequently buy more than they need, often because of the reduced price of the products or by taking advantage of bulk quantities, thereby transferring the problem of food waste from the retailer to the consumer level.

The model presented here in this article is dissimilar to any previous work and is new and unique in its intention and process, which is to reduce the total amount of food waste occurred in the retail and consumer supply chain together.

4. Food waste statistics and the model input

A survey of 330 participants who live or work in the vicinity of Naresuan University, Phitsanulok, Thailand was conducted. Their ages range between 18 and 55 years. There were 141 male participants (42.7%) and 189 female (57.3%). Our results showed that approximately 14% of the food purchased by consumers is discarded as waste. There was little difference between the male and female participants in this behaviour. Table 1 also illustrates that the level of income is likely to have an impact on the percentage of food waste, with the percentage of waste increasing with higher levels of income. The percentage of food wasted also varies significantly between food types, with up to 80% of food wasted in some food types in the lower income categories.

Input data for our mathematical model was also collected. Our intention was to identify consumer buying and consumption behaviours. Some of the questions in our survey questionnaire covered similar factors taken from previous studies [1], [3], [4], [8]. For each question, the participants rated their behaviour according to a Likert Scale, with the ratings from Highly Agree to Highly Disagree. These responses varied in their indication of a Positive response or a negative response. Taking an example from Table 2, a response of 5 to the question on using a prepared shopping list would be seen as having the positive outcome of reducing subsequent food waste, whereas a response of 5 to the question on buying a lot of the product to get a discount or sale promotion would be seen as having a negative impact, resulting in higher food waste.

Table 1. Percentage of food waste by types of food and income

Income	Percentage of food waste by	Types of food							Overall percentage by income
		Ready to eat (made-to-choose)	Thai fast food (made-to-order)	Raw ingredient	Desserts	Fruit	Drinks in sealed package	Fresh drinks	
Low	Average	13	11	13	12	12	10	11	12
	Max	80	70	60	50	60	50	60	61
Medium	Average	17	13	19	13	10	14	11	14
	Max	60	50	60	70	50	60	60	59
High	Average	22	23	24	16	10	15	13	18
	Max	70	60	70	70	30	50	60	59
Overall percentage by type of food		18	16	19	14	11	13	12	14

Table 2. List of questions for analysing the buying and consuming behaviours

	List of questions concerning buying and consuming food	Impact on food waste Reduction
Buying behaviour	1. Use a shopping list	Positive
	2. Buy according to the shopping list	Positive
	3. Like to buy reduced price food	Negative
	4. Buy a lot to get discount or sale promotion	Negative
	5. Buy a lot so you do not need to buy often	Negative
	6. Buy food as seen on advertisement	Negative
	7. Buy food as other people suggested	Negative
	8. Like to try different type of food	Negative
Consuming behaviour	1. Only eat food that is still fresh	Negative
	2. Discard leftover food after each meal	Negative
	3. Keep leftover food for the next consumption	Positive
	4. Discard fruit with flaws	Negative
	5. Understand the different between “Expire date” and “Best before”	Positive

Finally, the total score was transformed to the appropriate range to represent the coefficients of the consuming and buying behaviours, as shown in Table 3. As well, the participants were separated by gender and income into 3 groups per gender based on income levels; 6 groups overall. The coefficients for each group were statistically analysed for their probability distribution using Kolmogorov-Smirnov nonparametric tests. The coefficients of all groups were found to significantly fit with either a Normal distribution or a Poisson distribution. We pragmatically used the Normal probability distribution as its inverse function was available on our spreadsheet software. Table 4 shows the coefficients that were used as input into our example model to be discussed in Section 6.

For the retailers’ level, we interviewed a local convenience store owner regarding vegetables, fresh meat and bakery as the prominent perishable food types. The numbers of SKUs canvassed were 82 for vegetables, 70 for fresh meat products and 100 bakery products. The SKU’s selected covered package sizes as well as food type, brand and, in the case of vegetables, varieties. Our finding that over 24% of packed vegetables was regularly unsold and discarded by the store. The figure for packed fresh meat was nearly 3% and 19% for bakery.

For the purpose of discussing and demonstrating our model (in the next Section) we chose one type of packed vegetable, the stock level of which was reviewed every day. The order-up-to level was 8 units. The store’s distribution center could see point-of-sale data and used it to determine the amount to be sent to the store each day. The delivery arrived the next day.

Table 3. An example of converting and transforming of the rating scores from a single questionnaire

	Question number	Example score	Converted score	Total score	Transform by	Transformed score
Buying behaviour	1 2 3 4 5 6 7 8	2 1 4 4 3 2 2 4	4 5 4 4 3 2 2 4	28	dividing by 23	1.22
Consuming behaviour	1 2 3 4 5	5 1 4 3 5	1 5 4 3 5	18	dividing by 8	2.25

Table 4. Resulted probability distribution for the coefficients of consuming and buying behaviours

Group	Number of participants	Income	Gender	Probability distribution for the coefficients of	
				consuming	buying
1	90	Low	Male	N(1.95, 0.36)	N(1.05, 0.16)
2	105	Low	Female	N(1.89, 0.41)	N(1.05, 0.17)
3	43	Medium	Male	N(1.84, 0.40)	N(1.03, 0.16)
4	62	Medium	Female	N(1.90, 0.34)	N(1.01, 0.17)
5	8	High	Male	N(2.02, 0.33)	N(0.93, 0.19)
6	22	High	Female	N(1.88, 0.38)	N(0.98, 0.16)

Note: N(μ, σ) denotes Normal distribution with the means equal to μ and the standard deviations equal to σ.

5. Mathematical model

We considered a two-level supply chain with groups of consumers and a retailer as shown in Figure 1, where

G is the number of groups of consumers,

n_g is the number of population of group g that buy the certain type of product from the particular retail store and

T is the number of time period being studied.

A simple mathematical model can be constructed using balance equations as follows.

The total food waste of the supply chain at period *t* described as

$$FW_t^{sc} = FW_t^r + FW_t^c. \quad (1)$$

Assuming that the product has a unit expiry date, the food waste equation for retailer level at period *t*, FW_t^r, is given by

$$FW_t^r = O_t^r - D_t^c. \quad (2)$$

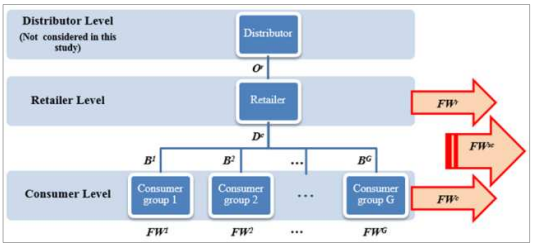


Figure 1. Model representation with some important variables

O_t^r denotes the amount of product received at the beginning of period *t*. D_t^c expresses the consumer demand for period *t*, which is explained in Eq. (7).

FW_t^c is food waste at the consumer level at period *t* given by

$$FW_t^c = \sum_{g=1}^{G} n_g \cdot FW_t^g. \quad (3)$$

FW_t^g is the average amount of food waste created by an individual of group g in period *t* calculated as

$$FW_t^g = B_t^g - C_t^g. \quad (4)$$

B_t^g denotes the amount of product bought from the retail store by an individual of group g in period *t* calculated as

$$B_t^g = \left\lceil \frac{\emptyset^g \cdot Min}{Size} \right\rceil \cdot Size. \quad (5)$$

$\emptyset^g$ is the coefficient of buying behaviour for group g as presented in Table 4. Min is the minimum requirement of a certain type of food according to the type of product being studied. For example, if the product of interest is packed vegetables, we can use the minimum daily dietary requirement of that vegetable (implying level of consumption). This requirement may differ between gender and consumer age. $Size$ is the size (or weight) of the unit of sale. The sign ⌈ ⌉ is for rounding up to find a number of sale units being bought. The total amount bought by an individual is the multiplication between the number of sale units and the size of the unit of sale.

In Eq. (6), C_t^g denotes the amount of product consumed by an individual of group g in period *t* :

$$C_t^g = \delta^g \cdot Min. \quad (6)$$

where δ^g is the coefficient of consuming behaviour for group g presented in Table 4.

Finally, D_t^c can be expressed as

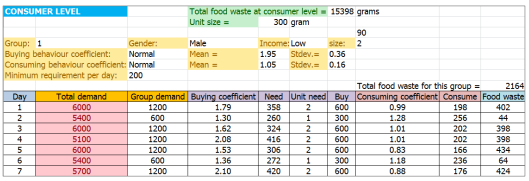
$$D_t^c = \sum_{g=1}^{G} B_t^g. \quad (7)$$

6. An example spreadsheet model

We used the mathematical expressions from Section 5 to model our supply chain in a spreadsheet. We set the number of groups of consumer, *G* equal to 6 and the number of time periods being studied, *T*, equal to 7 days. The probability distributions for the coefficients are set according to Table 4. Figure 2 is our spreadsheet model using one sheet for each of consumer level, retailer level and summary.

We investigated the impact of the size of a unit sale by varying the size between 50 and 550 grams. We performed 100 replications for each size. The average amounts of food waste are plotted in Figure 3. The results showed the impact of unit size on total food waste. The lowest total food waste was 282.7 kilograms at the 350-gram unit size, although the level of consumers' food waste at this size was the highest, but was compensated by the retailer's food waste at this size being the lowest, resulting in the lowest total food waste.

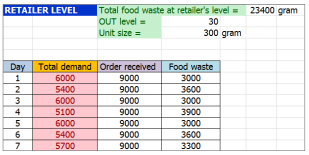
Note that the experiment was done under a certain inventory replenishment policy. This policy did not allow for shortages or backorders. Therefore, abundant inventory was kept at the retailer to ensure that the consumer would always obtain the whole order.


CONSUMER LEVEL

Total food waste at consumer level = 15398 grams
Unit size = 300 gram
90
Group: 1 Gender: Male Income: Low size: 2
Buying behaviour coefficient: Normal Mean = 1.95 Stdev.= 0.36
Consuming behaviour coefficient: Normal Mean = 1.05 Stdev.= 0.16
Minimum requirement per day: 200
Total food waste for this group = 2164

Day	Total demand	Group demand	Buying coefficient	Need	Unit need	Buy	Consuming coefficient	Consume	Food waste
1	6000	1200	1.79	358	2	600	0.99	198	402
2	5400	600	1.30	260	1	300	1.28	256	44
3	6000	1200	1.62	324	2	600	1.01	202	398
4	5100	1200	2.08	416	2	600	1.01	202	398
5	6000	1200	1.53	306	2	600	0.83	166	434
6	5400	600	1.36	272	1	300	1.18	236	64
7	5700	1200	2.10	420	2	600	0.88	176	424

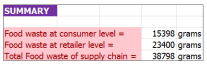
(a) Consumer level


RETAILER LEVEL

Total food waste at retailer's level = 23400 gram
OUT level = 30
Unit size = 300 gram

Day	Total demand	Order received	Food waste
1	6000	9000	3000
2	5400	9000	3600
3	6000	9000	3000
4	5100	9000	3900
5	6000	9000	3000
6	5400	9000	3600
7	5700	9000	3300

(b) Retailer level


SUMMARY

Food waste at consumer level = 15398 grams
Food waste at retailer level = 23400 grams
Total Food waste of supply chain = 38798 grams

(c) Summary

Figure 2. An example spreadsheet model

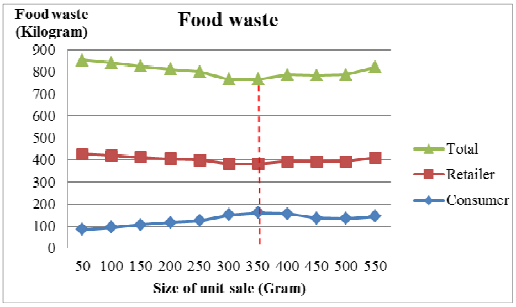


Figure 3. Impact of the size of a unit sale on supply chain's food waste

7. Conclusion

The key contribution of this study is the stochastic mathematical model for food waste reduction. We have not found any previous published work in this area that includes consumption and buying behaviour, inventory replenishment policy and the combination of food waste values from the 2-level supply chains. The probability distributions of the consuming and buying behaviours are the stochastic part of the model. We have used the model to show the impact of the size of a unit sale on the total food waste. Clearly, identifying the appropriate unit size of products can help reduce food waste in practice.

It is understood that not all products available in shops and supermarkets are highly perishable, and many have lengthy use-by-dates. Our model assumes the simplicity of a very short unit shelf life, usually of one day, which correctly encompasses vegetables, and bakery products, but also can be seen to include fresh meat products, seafood and some dairy products. To include a shelf life longer than this would certainly make the mathematical model more complex, but extending the model to encompass longer use by dates may show more useful results. This, however, is the subject of future research on a model that already shows it usefulness in improving inventory management practices, and may be extended to replenishment planning. The impact of the variety of the sizes of a unit sale will be interesting as well. The study of the whole supply chain from consumer to supplier is another possible extension.

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